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Combined regional and local modelling for aquifer remediation at a uranium mining site in the Czech Republic

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Abstract Uranium has been mined in the area of Stráž pod Ralskem and Hamr (Czech Republic) since 1967. Initially, only deep-mining was used, then *in situ* chemical leaching was introduced. The latter has caused a groundwater contamination that endangers the drinking water supply in the immediate vicinity of the mining area and poses a long term threat to groundwater quality in a much larger area. A detailed investigation for the remediation of the aquifers is now considered necessary. The base of the investigation is the geological and hydrogeological data. A database has been set up in the Geographical Information System (GIS) ARC/INFO for efficient entering, checking, storing, manipulating and retrieving of data. The density effects and intricate geology require locally a detailed fully three-dimensional model. However, it is not possible to include the whole area of interest (180 km^2) in a 3D model. Therefore two models are used: the regional groundwater flow is modelled by means of TRIWACO (quasi 3D), whereas local modelling (fully 3D) is done by means of METROPOL. The ARC/INFO database, the regional TRIWACO model, the local METROPOL model and the interfaces for data transfer form together a so-called Contaminant Transport Information System (CTIS). The power of CTIS lies in the fact that the modelling necessary for the design of a remediation operation can be carried out efficiently by using one of the two models, depending on the specific question. Thus alternative remediation scenarios can be easily evaluated and with respect to their effectiveness.

INTRODUCTION

A large uranium deposit occurs in the northern part of the Czech Republic near Stráž pod Ralskem (Fig. 1). The uranium is present ca. 200 m below the ground surface. The exploitation started in 1967 by means of conventional deep-mining. Later, *in situ* hydrochemical leaching was introduced. A large number of injection and extraction wells has been implemented in some 30 so-called "leaching fields". A hydraulic barrier has been installed in-between the mines and the leaching fields. The barrier consists of

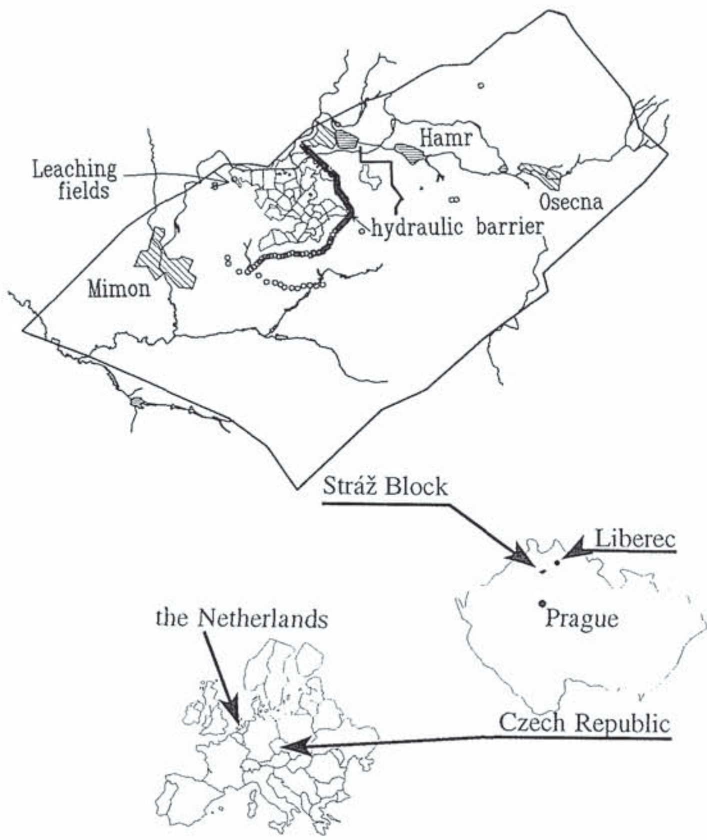

Fig. 1 Location of area of interest.

about 200 wells that inject water and prevent the migration of the leaching fluid away from the leaching fields towards the mines.

The chemical leaching of the uranium ore has caused a major groundwater contamination extending over ca. 20 km^2. Huge quantities of the strongly oxidizing and acidic leaching fluid have been injected and a large volume of this fluid is still present in the underground. Near the surface, the groundwater has been contaminated by spills and leakage from processing plants and transport pipe lines as well as defective casings of the injection and abstraction wells at the leaching fields. The major constituents of the contamination, both near the surface and at depth, are heavy metals (mainly aluminium) and sulphate. The average density of the leaching fluid is about 1050 kg m^{-3}, so that density differences have a significant influence on the groundwater flow. The deep contamination poses a long term threat to groundwater quality in a large surrounding area. The shallow contamination is of immediate concern for the local drinking water supply.

Remediation of the aquifers is now considered necessary. It will be a very large, expensive and time consuming operation. A detailed investigation of the present situation and of possible remediation scenarios is of paramount importance. The costs invested in the investigation will save expenses in the actual remediation. For this investigation, a Contaminant Transport Information System (CTIS) was developed.

HYDROGEOLOGY

The subsurface of northeast Bohemia consists of large blocks of mainly Cretaceous deposits, separated by large faults. The area where mining activities take place is part of the Stráž Block. In this block, minor faults and many volcanic intrusions are present. Although the geological situation is very complicated, the hydrogeology can be effectively described by a system of two aquifers (Fig. 2). The upper aquifer is the Turonian aquifer, the lower is the Cenomanian aquifer. The two aquifers are separated by the Turonian aquitard.

The hydraulic conductivity of the aquifers is essentially anisotropic, with the principle axes parallel to the Stráž Fault (northwestern edge of the Stráž Block).

In general, precipitation in the area exceeds evaporation, which results in an average net recharge of 125 mm year^{-1}. Furthermore, a number of creeks control the groundwater table in the Turonian aquifer. The direction of groundwater flow in the Stráž Block follows the general decline of the surface elevation from northeast to southwest.

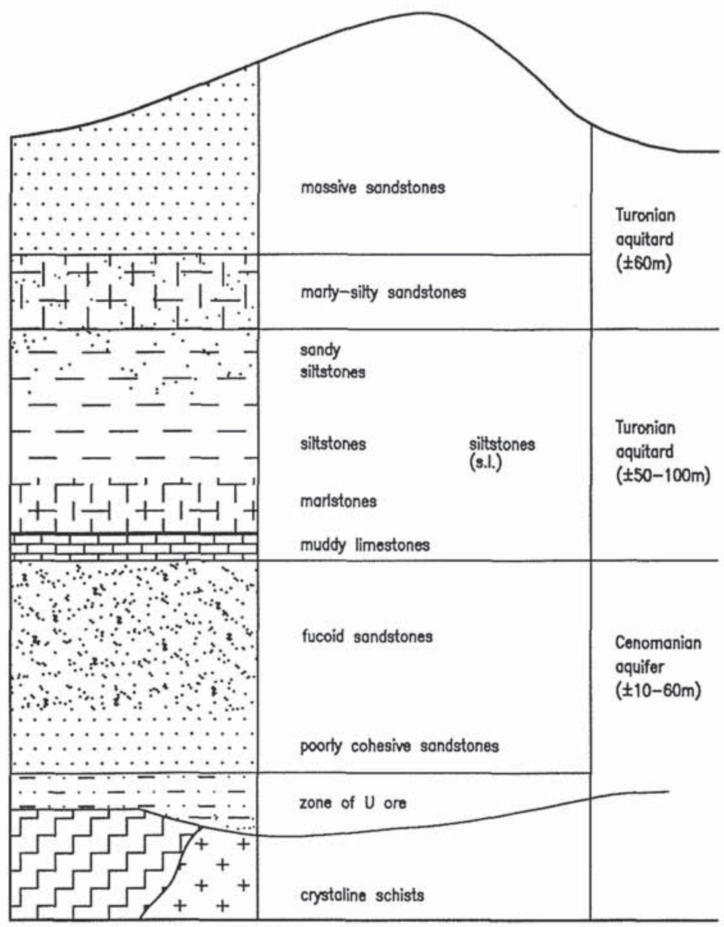

Fig. 2 Hydrogeology and geology of Stráž Block.

THE CONTAMINANT TRANSPORT INFORMATION SYSTEM (CTIS)

The extent and severity of the contamination in the Stráž pod Ralskem area require a thorough investigation prior to the design of any remediation operation. Numerical modelling of the groundwater flow provides a powerful tool for predicting the effectiveness of various remediation scenarios. The modelling makes use of the large amount of data that is available and of new data that will be collected in future. Therefore, the data should be stored in a database that is easily accessible and that also allows new data to be added. The use of one single database increases the clarity and transparency of the data stored. An other advantage of one single database lies in the fact that it allows easy combination of data and facilitates the checking of data consistency.

The entire Stráž Block (180 km^2) has to be covered by a numerical model. This is because of the large influence of the uranium exploitation operations on the groundwater flow and the lack of natural boundaries within the block. On the other hand, the groundwater density differences in the area of the leaching fields and the intricate geology require a large amount of detail and hence a high model resolution. These conflicting demands can not be met by one single numerical model. Therefore, the various aspects of the contamination and possible remediation scenarios will be investigated using different models.

Consequently, a large amount of information has to be transferred between the database and the models and between the models. To ensure efficient data transfer and to avoid the introduction of errors, the Contaminant Transport Information System (CTIS) was developed, combining the models and the database.

The information system consists of the following components (Fig. 3):

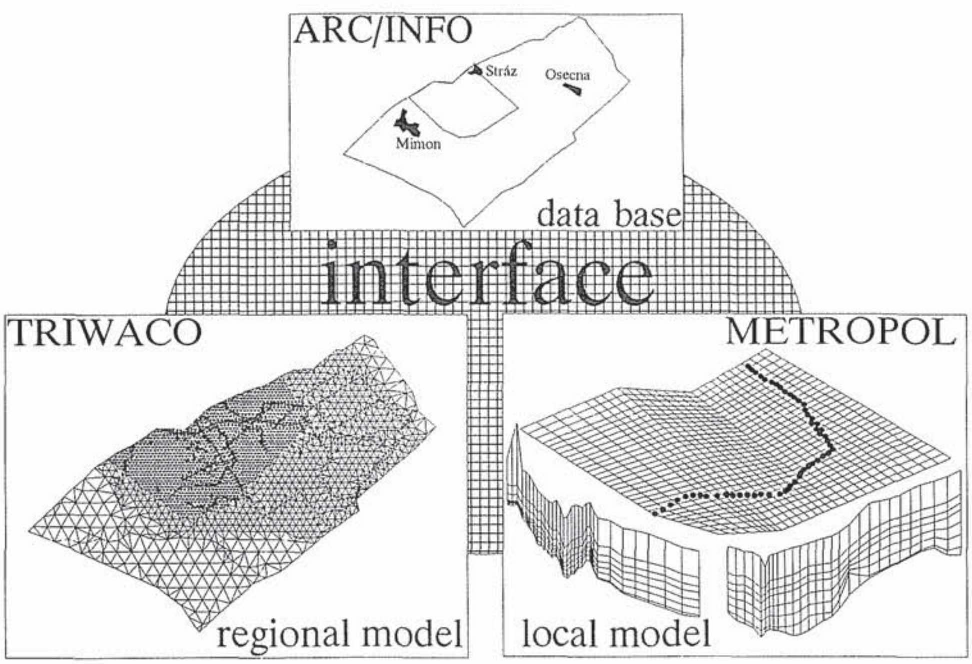

Fig. 3 Contaminant Transport Information System.

- a database, set up in the Geographical Information System ARC/INFO;
- a regional groundwater flow model using TRIWACO;
- a local groundwater flow and contaminant transport model using METROPOL;
- a GIS-model interface between ARC/INFO, TRIWACO and METROPOL.

The Contaminant Transport Information System is installed on a workstation connected with a PC. Most of the interfacing programs can be run on both the workstation and the PC. Both systems can also be used to run the TRIWACO model. The ARC/INFO database and programs and the METROPOL programs, however, can be run on the workstation only.

In the following sections, the components are discussed. First, the ARC/INFO database is addressed. Subsequently, the two hydrogeological models TRIWACO and METROPOL are dealt with. Finally, the GIS-model interface is described.

ARC/INFO DATABASE

At the Diamo company, data used to be stored in several locations, physically near the people that used and managed it. This was an efficient way for controlling the various elements of the uranium exploitation. However, it did not allow for intensive data checking and the data, available at different locations, could be inconsistent.

For the investigation of remediation activities, a central database was considered necessary. It was decided to bring all data together in a database in ARC/INFO. The Geographical Information System (GIS) ARC/INFO has been selected, since most data are related to a particular location, and interpolation between the point data in the database is very important. Moreover, ARC/INFO is very flexible and powerful in the processing of data and in generating output of the data required for e.g. groundwater models.

The database is set up to contain the large number of data that has been collected in the area around Stráž pod Ralskem over the years of exploration and exploitation. A large number of boreholes (ca. 15 000) has been drilled and the elevations of the successive geological strata have been measured.

About 1000 of these boreholes are used as observation wells. In these wells, piezometric data and water quality data have been recorded. Furthermore, a large number of wells are part of the leaching systems of the leaching fields. Here data are available on solute concentrations and on the amount of injected and abstracted fluid. The hydraulic barrier surrounding the leaching fields consists of injection wells, for which injection rates have been recorded. Also more general data are available, such as the geometry and discharge of surface water streams, surface elevations and groundwater recharge.

TRIWACO MODEL

The purpose of a regional groundwater flow model is to assess regional impacts of the mining and leaching operation and of possible alternatives for terminating this operation and for aquifer remediation.

Because of the scale of the problem and the fact that the differences in fluid density do not influence the regional flow very much, a quasi three-dimensional model is an adequate tool for the regional flow. It is far less time consuming than a fully three-dimensional model for regional flow and not less accurate. The finite element package TRIWACO (IWACO, 1992) was selected because:

- the geometry of a model is very flexible and nodal distances can be differentiated easily, due to its triangular elements;
- surface water interaction can be modelled accurately;
- several types of topsystems are available for modelling of the recharge;
- it is a very complete package, including various (graphical) output options, a module for pathline tracing and an interface for data exchange with ARC/INFO;
- it has proven to be reliable in a large number of other modelling studies.

The model area selected coincides with the Stráž Block. The edges of the block are natural discontinuities, much more pronounced than the volcanic features within the block. Moreover, these edges are remote enough from the mining area that simple boundary conditions can be used to represent the influence of the faults and the area beyond the faults on the groundwater flow.

Vertically, the model comprises three aquifers, separated by two aquitards. The first (top) aquifer represents the Turonian aquifer, whereas the Turonian aquitard acts as the first aquitard. The Cenomanian aquifer is divided into two aquifers: the fucoid sandstones and the poorly cohesive sandstones. The second aquitard, separating the two Cenomanian aquifers, represents the resistance to vertical flow between these aquifers. The top of the wash-out zone and the Cenomanian fresh water deposits is considered to be the base of the regional groundwater system. The hydraulic conductivity of these layers is two orders of magnitude less than that of the overlying layers so that regional flow in these layers is negligible.

Point sources, located at the nodal points of the model grid, represent the injection and abstraction wells. Each leaching field is represented by one well only, abstracting or injecting the net amount of the leaching field wells. The injection wells of the hydraulic barrier are included separately in the model, as are the wells of the drinking water abstractions of Mimoň and Osečná.

The drainage system of the mine Hamr I is incorporated in the model as a line sink, whereas the other mines are represented by point sources. Also the surface water system is modelled by line sinks, of which the flux is determined by the calculated head in the aquifer and specified values for the water level, the infiltration or drainage resistance and the width.

Groundwater recharge rate over the whole area is provisionally set to 125 mm year^{-1}.

The finite element mesh of the regional model (Fig. 3) contains 2537 nodes and 4925 elements. Calculated hydraulic heads are given in Fig. 4 for the Turonian aquifer and the Cenomanian aquifer.

METROPOL MODEL

To study the local impacts of the mining and leaching operations and their prospective termination, a local fully 3D groundwater flow and solute transport model is developed. This model simulates the transport of contaminants at relatively short distance from the leaching fields and takes into account the fluid density differences.

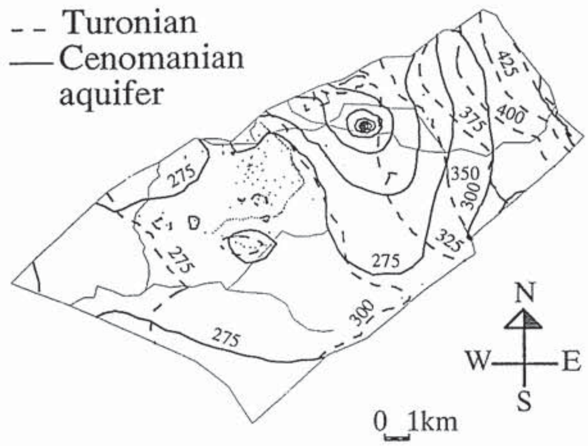

Fig. 4 Piezometric heads calculated by TRIWACO.

CTIS uses the existing software package METROPOL (Sauter *et al.*, 1993), which was developed by the Netherlands National Institute of Public Health and Environmental Protection (RIVM). METROPOL was selected because:

- it is one of few packages that can model fully three-dimensional groundwater flow with varying density depending on solute concentrations;
- it is able to simulate the transport of solutes, taking into account linear equilibrium sorption, dispersion and decay;
- the package is geared towards the simulation of radioactive processes;
- it allows for fairly flexible geometries, since the finite elements are distorted cubes;
- it has proven to be reliable and has been verified in the framework of a number of international validation projects.

The local model, set up initially for testing of the Contaminant Transport Information System, horizontally extends over an area comprising the leaching fields, covering the area containing the injected leaching fluid. Boundary conditions for the local model are obtained by interpolation of calculated heads from the regional TRIWACO model. These hydraulic heads are converted to pressure values at the centre of the corresponding aquifer, taking into account the local groundwater density variations. Assuming a hydrostatic pressure distribution at the boundary of the model, the computed pressure values are extrapolated vertically to obtain an approximate pressure distribution.

Vertically, the model comprises seven layers, together representing the Cenomanian aquifer. The top of the local model is set at the base of the Turonian aquitard. The boundary flux, which is rather limited, is derived from the regional model. The top of the crystalline rock is the base, unlike the regional model. The wash-out zone and the Cenomanian fresh water deposits are included in the local model since these formations contain the uranium ore and, hence, a source of contamination.

Similar to the regional model, each leaching field is represented by a single well. The vertical extent of the well is limited to the length of the well screen in the leaching fields. The wells of the hydraulic barrier are incorporated in the model with a well screen extending vertically over the whole aquifer.

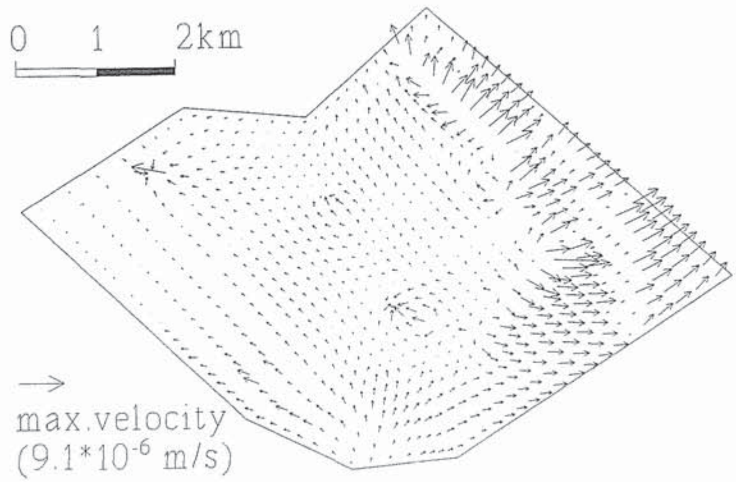

Fig. 5 Velocities calculated by METROPOL.

The finite element mesh of the local model (Fig. 3) contains 6944 nodes and 5670 elements. Graphical output of the METROPOL model consists of horizontal or vertical cross-sections with contours for pressure values and contaminant concentrations, pathlines or a velocity field. A vector plot of groundwater flow velocities is presented in Fig. 5. Figure 6 shows two vertical cross-sections of the model with velocity vectors and concentration contours.

GIS-MODEL INTERFACE

The transfer of data between the database and both the regional TRIWACO and local METROPOL model is carried out by the GIS-model interface. The location of the boundaries, wells and streams is transferred from the ARC/INFO database to the mesh generator of TRIWACO. After the mesh has been constructed, the coordinates of the nodal points of the finite element mesh are imported into ARC/INFO to enable the allocation of the necessary parameter values to the nodes. Once the parameter values have been transferred to TRIWACO, the model simulations can be carried out. The results of the simulations can be passed over to ARC/INFO and can be used for the local METROPOL model (to provide initial and boundary conditions).

Similar to the procedure for the regional model, initial data needed for the generation of the finite element mesh have to be extracted from the database and transferred to the mesh generator of METROPOL. These data are used to construct a two-dimensional finite element mesh, consisting of quadrilaterals. In ARC/INFO the elevations of the successive geological strata are determined for each node and exported to the 3D mesh generator of METROPOL. Next, ARC/INFO is used to assign the parameter values to the nodal points or to the elements.

Initial and boundary conditions for the METROPOL model are derived from the simulation results of the regional model. Hydraulic heads of the regional TRIWACO model, stored in the ARC/INFO database, are exported and, combining these with data on the groundwater density, a three-dimensional pressure field is computed. This

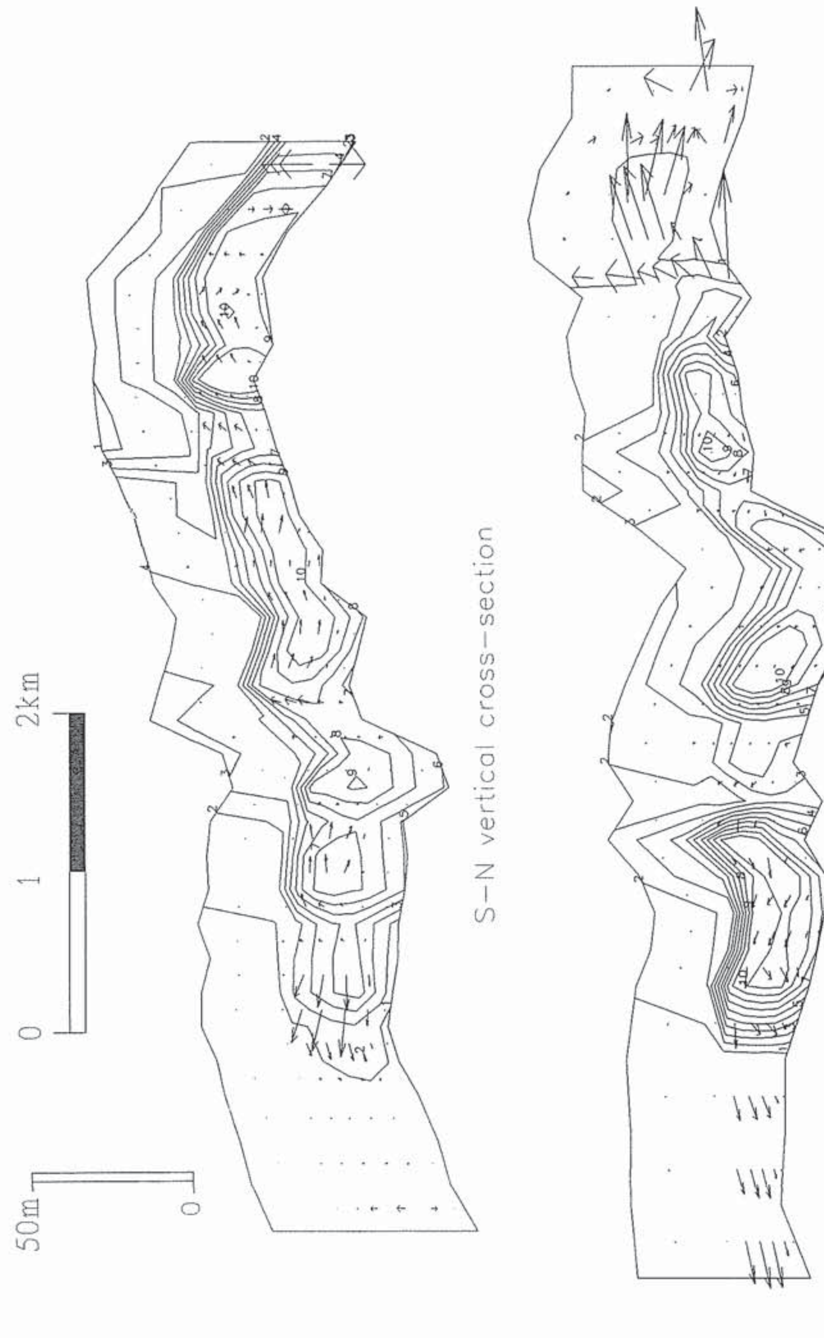

Fig. 6 Cross-sections with velocities and concentration contours (METROPOL).

pressure field is used as initial condition for the simulations carried out with the METROPOL model. Boundary conditions, consisting of prescribed pressures, are obtained from the initial pressure field and kept constant in time. However, time dependent boundary conditions can be obtained similarly from a transient simulation with the regional TRIWACO model.

CONCLUDING REMARKS

The Contaminant Transport Information System has an open structure. This facilitates the input of new (types of) data and incorporation of other simulation programs, to model for instance hydrochemical processes, surface water flow or ecological impact.

ARC/INFO provides simple tools to bring all available data together and to visualize results. Thus, the Contamination Transport Information System ensures a solid base for risk analysis of remediation strategies that will have to be carried out for the Stráž pod Ralskem uranium mining area. The fact that the system contains both a regional and a local model allows efficient use of the available data and minimizes the modelling efforts. Combination of model results with other data in the ARC/INFO database allows one to evaluate alternative remediation scenarios easily and with regard to their consequences and effectiveness. Thus comparison of such scenarios has become possible.

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REFERENCES

IWACO (1992) *Manual for TRIWACO version 6.0.* IWACO Consultants for Water and Environment, Rotterdam, The Netherlands, December 1992.

Sauter, F.J., Leijnse, A. & Beusen, A.M.W. (1993) User's guide METROPOL. *Report No. 725202003, RIVM, Bilthoven, The Netherlands.*